NATIONAL ACADEMY OF SCIENCES OF UKRAINE

INSTITUTE FOR NUCLEAR RESEARCH

Manuscript

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UDK 539.165

Double beta decay of $^{64,\ 70}$Zn and $^{180,\ 186}$W isotopes

01.04.16 – physics of nuclei, elementary particles, and high energies

A thesis for the Ph.D. Degree (Physics and Mathematics)

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Kyiv – 2009

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ABSTRACT

The results of the experimental investigations of double beta processes in Zinc and Tungsten isotopes with the help of middle volume (117 g, 168 g and 699 g) low-background $ZnWO_4$ crystal scintillators are presented. The experiment was carried out in the low-background "DAMA/R&D" set-up at the Gran Sasso National Laboratories of the INFN (Italy) at a depth of ≈3600 m w.e. The total measurement time exceeds ten thousand hours. New improved half-life limits on double electron capture and electron capture with positron emission in ^{64}Zn have been set: $T^{2\nu 2K}_{1/2}(^{64}\mathrm{Zn}) \geq 6.2(6.3) \times 10^{18}$ yr, $T^{0\nu 2\varepsilon}_{1/2}$ $(^{64}\mathrm{Zn}) \geq 1.1(2.8) \times 10^{20}$ yr, $T^{2\nu\varepsilon\beta^+}_{1/2}(^{64}\mathrm{Zn}) \geq 0.7(2.1) \times 10^{21}$ yr, and $T^{0\nu\varepsilon\beta^+}_{1/2}(^{64}\mathrm{Zn}) \geq 4.3(5.7) \times 10^{20}$ yr, all the limits are at 90% (68%) C.L. The positive indication on the $\varepsilon\beta^+$ decay of ^{64}Zn with $T^{(2\nu+0\nu)\varepsilon\beta^+}_{1/2}$ $(^{64}\mathrm{Zn}) = (1.1 \pm 0.9) \times 10^{19}$ yr suggested in [Appl. Radiat. Isot. 46 (1995) 455–456] is fully discarded by the present experiment. To date only two nuclei (^{40}Ca and ^{78}Kr) among 34 potentially "$2\beta^+$ active" nuclides were studied at the similar level of sensitivity. However, it is worth noting that the theoretical predictions are still higher.

The half-life limits on the 2β processes in ^{70}Zn, ^{180}W, and two neutrino mode of $2\beta^-$ decay in ^{186}W established in the present work on the level of $10^{17} - 10^{20}$ yr are one order of magnitude higher than those set in previous experiments.

Energy resolution, relative light output, α/β ratio, decay time, pulse-shape discrimination between α particles and γ rays (β particles), and radioactive contamination of $CdWO_4$, $PbWO_4$ (undoped, and doped by F, Eu, Mo, Gd, S), and $ZnWO_4$ crystal scintillators were studied. Pulse-shape discrimination ability of $PbWO_4$ and $ZnWO_4$ crystal scintillators were realized for the first time. The first result of low-background measurement with small volume $ZnWO_4$ (mass of 4.5 g) gave reasons for extensive research work in the Institute for Scintillation Materials (Kharkiv, Ukraine) in order to optimize the growth conditions with the aim of producing high quality large-volume $ZnWO_4$ crystal scintillators. Applicability of these scintillators to search for double beta decay was proved.

The time-amplitude analysis, the pulse-shape discrimination, and the Monte Carlo simulation were applied in addition to the ICP-MS measurements to estimate radioactive contamination of the $ZnWO_4$ detectors. We have found $ZnWO_4$ crystal scintillators extremely radiopure detectors with typical contamination at the level of μBq/kg (^{228}Th and ^{226}Ra), ≤ 0.06 mBq/kg (^{210}Po), total α activity (U/Th) 0.2−0.4 mBq/kg, ≤ 0.4 mBq/kg (^{40}K), ≤ 0.05 mBq/kg (^{137}Cs), ≤ 0.4 mBq/kg (^{90}Sr-^{90}Y), ≤ 0.01 mBq/kg (^{147}Sm), and ≤ 3 mBq/kg (^{87}Rb). Our investigations with zinc tungstate crystals have demonstrated a good potential of $ZnWO_4$ scintillators for the next generation double beta decay and cryogenic dark matter experiments, in particular for EURECA project, where a multi-element target with the total mass up to 1 t is planned for confirming dark matter signal. High abundance of ^{64}Zn (48.3%) allows to build a large scale double beta experiment without expensive isotopic enrichment. An experiment involving ≈10 tons of $ZnWO_4$ crystals (9×10^{27} nuclei of ^{64}Zn) could reach the half-life sensitivity up to 3×10^{28} yr (supposing zero background during ten years of measurements). Such a sensitivity could contribute to our understanding of the neutrino mass mechanism and right-handed currents in neutrinoless processes. The two neutrino double electron capture should be surely observed: in accordance with the theoretical expectations $T_{1/2}$ for $2\nu 2\varepsilon$ process is predicted on the level of $10^{25} - 10^{26}$ yr.

A new project of high sensitive $2\beta^-$ experiment was proposed. For this purpose, the new detection system with high light collection and energy resolution was developed, and $PbWO_4$ crystals were also discussed as high-efficiency 4π active shield and light guides in ^{116}Cd double beta decay experiment with enriched $^{116}CdWO_4$ crystal scintillators. The sensitivity of such an experiment (in terms of the half-life limit) is estimated as $lim\ T_{1/2}^{0\nu 2\beta^-}(^{116}\mathrm{Cd}) \approx 10^{26}$ yr, which corresponds to the effective Majorana neutrino mass $\langle m_\nu \rangle \approx 0.07$ eV.

Keywords: Double beta decay, ^{64}Zn, ^{70}Zn, ^{180}W, ^{186}W, low-background experiment, scintillation detector, half-life limit, radioactivity, $CdWO_4$, $PbWO_4$, $ZnWO_4$.

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